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Thermal response of chalcogenide microsphere resonators

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Abstract. **A chalcogenide microsphere resonator (CMR) used for temperature sensing is proposed and demonstrated. The CMR is fabricated using a simple technique of heating chalcogenide glass and allowing the molten glass to form a microsphere on the waist of a tapered silica fibre. The thermal responses of the CMR is investigated and compared to that of a single-mode-fibre (SMF) based microsphere resonator. It is observed that the CMR sensitivity to ambient temperature changes is 8 times higher than that of the SMF-based microsphere resonator. Heating the chalcogenide microsphere with a laser beam periodically turned on and off shows periodic shifts in the transmission spectrum of the resonator. By injecting an intensity-modulated cw signal through the resonator a thermal relaxation time of 55 ms is estimated.**

Keywords: *chalcogenide, microsphere resonator, temperature sensor.*

1. Introduction

Microsphere resonators have recently become the focus of significant research efforts due to their potential applications in nonlinear optics and optical sensing applications. Microsphere resonators have many unique and interesting properties, such as the ability to strongly confine light within a micro- or nanocavity. This allows for greater interactions between the circulating light and the cavity material, which is useful for studying a variety of linear and nonlinear optical phenomena such as Raman generation [1 – 3]. The evanescent field surrounding the microsphere can also be exploited for a variety of sensing applications, such as detection of biological constituents [4], because strong interaction of the evanescent fields with microorganisms at close proximity with the microsphere surface can be observed as resonance shifts in the transmission spectrum [5]. Furthermore, other sensor applications can also be realised with microsphere resonators, such as measurement of gas compositions and temperatures [6]. As with biological constituents, the microsphere resonator is highly sensitive to the gas temperature variation, and direct contact of the resonator with the ambient gas, allows for changes to be evaluated from the magnitude of the resonance shift in the transmission spectrum [7]. In addition, the resonance wavelength of the microsphere resonator also varies with temperature changes, and by heating the resonator with a laser periodically turned on and off, the thermal relaxation of a resonator can be estimated [8].

Typically, microsphere resonators are fabricated using silica based single-mode fibres (SMFs). However, the fabrication of microsphere resonators has also been reported using other materials such as lead silicate fibres [9], chalcogenide fibres [10, 11] and polymer coated silica fibres [6]. Microsphere resonators fabricated with these materials exhibit different thermo-optical properties, thermal expansion and optical nonlinearity characteristics as compared to microspheres fabricated using silica SMFs. The fabrication of microsphere fibres with chalcogenide glass is of particular interest. Chalcogenide glass is amorphous and comprised of a composite of chalcogen elements (S, Se or Te) and network forming elements (As, Ge, Si, Sb and P). This material has found many applications in optics and photonics such as spectroscopy, fast optical signal processing for optical fibre networks and industrial IR-sensing. The high refractive index of chalcogenide glass, which is approximately 2.4 to 2.7, makes it a highly potential candidate for the fabrication of microsphere resonators, as the high refractive index allows good light confinement within the microsphere.

In this work, application of a silica conical tapered fibre with a chalcogenide microsphere resonator (CMR) as a temperature sensor is proposed and demonstrated. The temperature response and sensitivity of the CMR is determined to be much higher as compared to that of a silica microsphere resonator. Subsequently, the thermal relaxation of the CMR is investigated based on a modified heating technique as compared to the approach by Sumetsky et al. [8], whereby as the CMR is heated by turning periodically the power of the incident laser beam on and off, a cw laser signal with a fixed wavelength is injected into the microsphere and the intensity-modulation by the shifted transmission spectrum is obtained. The output power of the microsphere resonator is analysed using a mathematical model and the thermal relaxation/response time is determined.

2. Fabrication of a chalcogenide microsphere

In fabricating the CMR, we placed a short segment of chalcogenide fibre (~0.5 mm) on a clean glass slide and heated on a hot plate to above its melting temperature, which is approximately 350 °C. After one minute of heating, the chalcogenide fibre transforms into molten glass, and a 3 – 4-cm-long silica

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tapered fibre manufactured based on heat-and-pull technique is dipped into a small volume of molten chalcogenide glass and drawn onto the tapered fibre. Figure 1a shows the microscope images of the chalcogenide glass adhered on a ~7 μm-diameter tapered fibre. To improve the spherical geometry of the chalcogenide microsphere at the tapered fibre tip, the chalcogenide glass is heated again and melted by placing it at a distance of 5–8 mm from the electric heater with temperature of 50 °C above its melting point. By exploiting the strong surface tension of the melt, the chalcogenide is turned into a spherical shape after several seconds of heating and the supporting tapered fibre is placed in the centre axis of the microsphere (Fig. 1b). In fabricating the CMR, its size can be controlled by choosing the initial volume of chalcogenide used, and if necessary reduced by dividing its mass using another silica tapered fibre while the chalcogenide glass is in molten form.

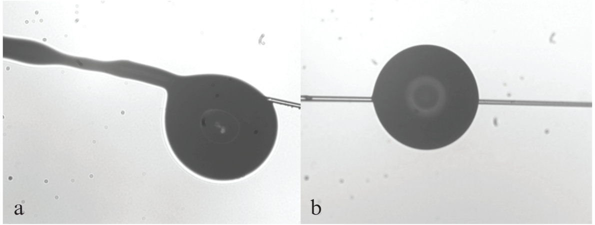

Figure 1. (a) Adhesion of chalcogenide glass on a supporting tapered fibre, and (b) improved spherical shape of the CMR with a diameter of ~178 mm.

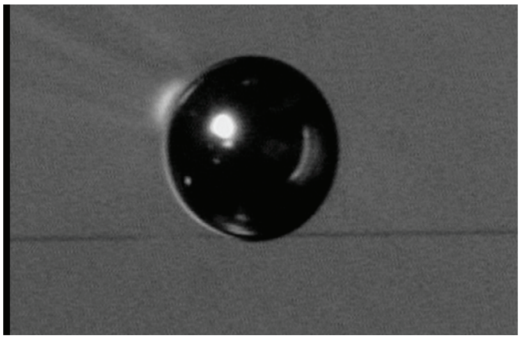

Figure 2. Microscope image of the CMR coupled with a tapered fibre.

The microscopic image of the CMR coupled with a tapered fibre is given in Fig. 2.

3. Temperature response

It is well known that the optical characteristics of glass are dependent on temperature [12]. In this regard, changes in the ambient temperature result in resonance wavelength shifts in the transmission spectrum, which can be described as a function of the thermo-optic and thermal expansion effects [12, 13]:

$$\frac{\Delta\lambda}{\lambda_0} = (\alpha_{\mathrm{TOC}} + \alpha_{\mathrm{TEC}})\Delta T, \tag{1}$$

where λ_0 is the operating wavelength; $\Delta\lambda$ is the resonance shift; ΔT is the temperature variation; and α_{TOC} and α_{TEC} are the thermo-optic coefficient and thermal expansion coefficient, respectively. The thermo-optic effect has a faster response time as compared to the thermal expansion effect [14] and this factor is taken into account in this investigation.

In determining the temperature response of the CMR, a small heating element was placed at a distance of 1 mm from the CMR that has been coupled to the waist of the biconical tapered fibre. The temperature was controlled by manipulating the driving electric current of the heating element. Figure 3 presents the temperature response of the CMR and the temperature response of an SMF-based microsphere resonator.

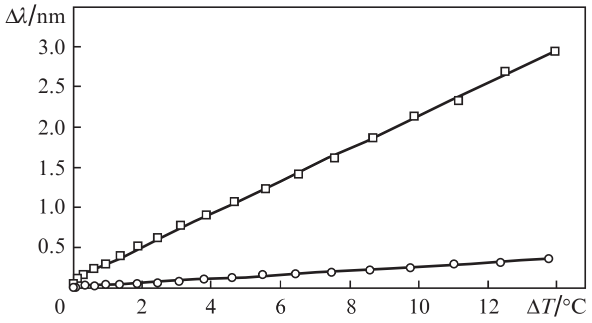

Figure 3. Resonance shift $\Delta\lambda$ as a functions of the temperature change for chalcogenide (squares) and silica (circles) microsphere resonators. The solid lines represent the linear fit to the experimental data.

The temperature is initially set at 24 °C (room temperature) and reaches a maximum of 39 °C when the driving current is $I = 2.0$ A. The experimental data clearly show that the wavelength shift is linearly proportional to the temperature change; therefore, the measured temperature sensitivity of the CMR is determined to be approximately 205 pm°C^{-1}. In comparison, the temperature sensitivity of an SMF-based microsphere resonator is eight times smaller and is approximately equal to 26 pm°C^{-1}.

4. Thermal relaxation

As well as the sensitivity, the response time or thermal relaxation of the proposed temperature sensor is critical if real-time temperature monitoring applications are to be considered. To investigate the thermal relaxation of the CMR, a 532-nm laser with a beam diameter of 2.3 ± 0.2 mm modulated as a square wave with an off-duty ratio of 33% is coupled into the CMR to provide heating. The output power of the 532-nm laser is 0.15 W with a modulation period of 0.94 s. Due to the small size of the CMR as compared to the laser beam diameter, it is assumed that the signal of the laser irradiating the CMR follows a square wave modulation. Because chalcogenide glass has high absorption for light in the visible range, the 532-nm laser light would be absorbed by the CMR and converted into heat. With heating turned on, the temperature of the CMR increases and the transmission spectrum shifts to the red by approximately 0.83 nm from the wavelength, corresponding to point B, to point A (Fig. 4), which corresponds to a temperature increase of 4 °C. With heating turned off, the temperature of the CMR decays to room temperature as the heat is dissipated and the spectrum returns to its original state. To simulate the probe signal intensity

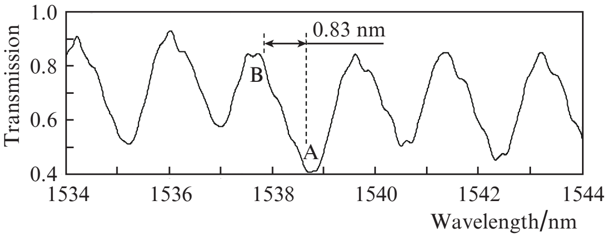

Figure 4. Transmission spectrum of the CMR at room temperature.

response with the change in the temperature, a single wavelength cw laser is used to irradiate the CMR at a selected resonance wavelength of 1538.6 nm (point A in Fig. 4).

The output from the CMR is observed to be modulated by the oscillatory-shifted spectrum corresponding to the 532-nm laser irradiation. If the transition between point A and B in the transmission spectrum is taken to be linear, the transmitted laser power is also assumed to be linearly modulated by the temperature variation. The rescaled output response depicted in Fig. 5 is the temperature variation of the CMR. The thermal relaxation of the CMR can be described adequately by the lumped system equation [15]:

$$\frac{\mathrm{d}T(t)}{\mathrm{d}t} = -\frac{1}{\tau}(T(t) - T_{\mathrm{r}}) + A(t), \tag{2}$$

$$T(t) = T_{\mathrm{r}} + \int_0^t \mathrm{d}t' A(t') \exp\left(\frac{t'-t}{\tau}\right), \tag{3}$$

where $A(t)$ is the periodic on/off heating as a function of time; $T(t)$ is the CMR temperature; T_{r} is the room temperature; and τ is the relaxation time. The experimental data in Fig. 5 are fitted with the theoretical curve with $\tau = 55$ ms. In the curve fitting, a small discrepancy can be observed particularly at the decaying part of the temperature curve. This discrepancy can be attributed to the imperfect linear transition between points A and B (Fig. 4). The temperature response observed is not instantaneous because of the time required for heat transfer within the CMR volume before it reaches thermal equilibrium. Therefore, the relaxation time of the CMR can be further reduced by using chalcogenide spheres of smaller volume to reduce the time taken to reach thermal equilibrium. Nevertheless, the short relaxation duration of 55 ms means that the proposed CMR is suitable for real-time temperature monitoring.

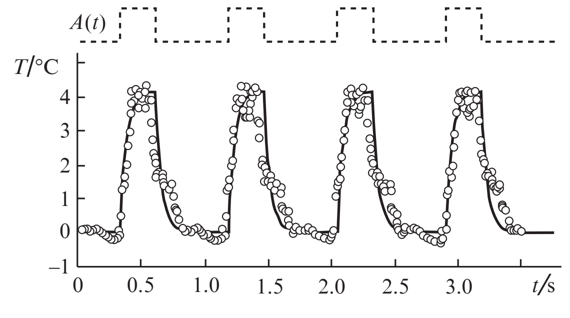

Figure 5. Time dependence of the CMR temperature: experimental data (circles) with fitted theoretical curve (solid line). The square wave with an off-duty ratio of 33% (dashed line) illustrates the corresponding heating by periodically turning the power of the laser beam on and off.

5. Conclusions

A simple fabrication technique of the CMR is demonstrated and its thermal response is investigated. Similar to the SMF-based microsphere resonator, the CMR shifts to the red as the temperature increases. However, the rate of the wavelength shift is 8 times higher compared to the SMF-based microsphere resonator. The CMR is also subjected to periodic on/off heating by a laser beam to induce oscillatory-shifted spectrum modulation, and the intensity modulation of a cw probe laser radiation transmitted through the CMR is measured. The wavelength of the cw laser is deliberately set to coincide with the linear transmission range of the CMR and the intensity of the cw laser is observed to be linearly modulated. By curve-fitting the output response of the CMR with a theoretical curve, the thermal relaxation time of 55 ms is estimated. An important advantage of the CMR lies in the area of temperature sensing, because it has a sensitivity of 8 times higher as compared to SMFs.

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